An European Tidal Gravity Profile over a 30° Latitude difference (Kevo - Bruxelles - Madrid).

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with 1 figure and 7 tables

Ducarme, B., Vieira, R., Kääriäinen, J., 1985 :
Proceedings of the Tenth International Symposium on Earth Tides.
pp. 199 - 212.

Abstract : Tidal gravity measurements have been performed in 1984-85 at Kevo (North Finland), Bruxelles and Madrid with two LaCoste-Romberg model G gravimeters transformed into zero method instruments. All gravimeters were normalized at Brussels.
According to the Wahr model, a thirty degrees latitude difference should produce more than one per cent decrease of the δ factor between Madrid and Kevo.
Due to the uncertainties in the oceanic loading computations we cannot derive firm conclusions for the semidiurnal waves.
The latitude effect is clearly seen on the diurnal waves between Bruxelles and Kevo but not between Madrid and Bruxelles. It may be concluded that local anomalies may conceal the latitude effect.

Keywords : Latitude effect, Indirect oceanic effect.

1. *Introduction*

Since Love (1911), it is well known that the tidal gravimetric δ factors are latitude dependent. Wahr (1981) calculated the coefficients of this dependence for different Earth models.

A first experimental confirmation was brought by Melchior (1983) who studied the worldwide distribution of the δ factors of the main tidal waves in function of the latitude. This analysis showed a good agreement in the slope of the regression line but a systematic disagreement of the order of one per cent for the constant term. Further studies confirmed that fact (Melchior, De Becker, 1983). However the scattering of the tidal results is very large compared to the investigated phenomenon (Fig. 1) and only stations at very high or very low latitude may significantly contribute to the determination of this latitude effect.(Vieira, R., 1981)

It is a reason why we decided to observe a tidal gravity profile extending over a range of 30° of latitude in Europe from Madrid (Spain) to Kevo (Finland). The forecasted latitude effect is larger than one per cent and reaches already 0.75 per cent between Brussels and Kevo (Table 1). Unfortunately, in the semidiurnal tidal band, the amplitudes become very low at high latitude (M_2 reaches only 10 μgal at Kevo, but 30 μgal at Brussels and 40 μgal at Madrid).

It is thus necessary to reach a precision better than 0.1 μgal on the correction of the oceanic indirect effects at Kevo, a precision which corresponds to 10 per cent of the computed effect. Such a precision is probably not insured due to the imperfect knowledge of the oceanic tides in the Arctic Ocean.

We must therefore mainly rely upon the diurnal earth tides which are twice larger than the semidiurnal ones at this latitude and which are disturbed by much smaller indirect effects : 10 per cent error in the loading computation will produce only an error of 0.1 per cent on the corrected δ factor of O_1.

In the southern segment of the profile the tidal amplitudes are larger but the indirect effects are also bigger in the semidiurnal band so that a 10 per cent error in the loading computation will also affect the corrected δ factor by one per cent for M_2 and only 0.1 per cent for O_1.

2. *Choice of the instruments and site selection*

The objective of the measurements being to reach a precision of a few thousandths on the measured tidal amplitudes and one tenth of a degree on the phases it was necessary to select the best available gravimeters.

In 1983, Van Ruymbeke succeeded in transforming LaCoste-Romberg model D and G gravimeters into zero method instruments, using Sato-Harrison principle (Van Ruymbeke, 1985; Harrison, J., Sato, T., 1983.).As a result the perturbations due to the tilt of the instrument are drastically reduced (Zhou Kungen and Van Ruymbeke, 1985). The sensitivity remains stable within one per cent in normal observing conditions while with non zero instruments a ten per cent variation was usual. As there is practically no more displacement of the beam, the elastic after effects of the spring are suppressed and it is no more necessary to correct the instrumental phase lags by adjusting a rheological model (Ducarme, 1975). We identify these zero methods instruments by the letters LCZ.

It was decided to perform parallel registrations with two instruments in Finland and to intercompare them at the Brussels Fundamental Station at the Royal Observatory of Belgium.

Kevo is the Northernmost available site in Finland. It is the location of a Subarctic Research Station depending from the Turku University. Technicians are working there all the year round and electrical generators provide emergency power in case of electrical failure. This site had been already occupied by the late Professor Honkasalo in 1972 with a Geodynamics gravimeter (Ducarme and Kääriäinen, 1980).

In Madrid there are two tidal gravity stations : one is located in the Campus of the Universidad Complutense and the other in the National Monument of Valle de los Caidos, some fifty kilometers from the city center. The two stations have been intercompared by using many gravimeters. For the facility of the maintenance it was decided to install the gravimeters at the University.

3. *Calendar of the Observations*

The profile started in march 1984 with the installation of two gravimeters in Kevo :

LCZ 402 belonging to the Royal Observatory of Belgium (ROB)

LCZ 665 belonging to the Instituto de Astronomia y Geodesia del Consejo Superior de Investigationes Cientificas (CSIC).

The LCZ 402 was already normalized in the Brussels system.

In september 1984, LCZ 665 was moved to Brussels for intercomparison and LCZ 402 to Madrid. In the same time the LCZ 487, a second belgian gravimeter, was installed in Madrid.

Finally in march 1985 all gravimeters returned to their home countries. A summary of the registration periods is given in Table 2.

4. *Improved Brussels System*

The so-called Brussels Tidal Gravity System (Ducarme, 1975) is based upon an accepted value for $\delta\ (O_1)$:

$$\delta\ (O_1) = 1.161$$

and phase differences :

$$\alpha\ (O_1) = -0.^\circ2, \qquad \alpha\ (M_2) = 2.^\circ8$$

These values were determined from observations performed between 1958 and 1970 using exclusively Askania gravimeters either of type GS11 or BN modified. With this normalization, which includes the inertial correction, the results of observations performed during the Trans European Tidal Gravity Profile (1970-1973) and the Trans World Tidal Gravity Profile (after 1973) fit well the Molodensky model I corrected for indirect oceanic effects computed from the Schwiderski maps (Melchior & alii, 1981).

The phase differences were confirmed independently by the Superconducting gravimeter (Ducarme, 1983) and by the LCZ gravimeters (Van Ruymbeke, 1985).

However, as already stated in the Introduction, a contradiction exists between the Brussels Tidal System and the most recent model for the body tides (Wahr, 1981). The debate is obscured by the fact that the inertial correction (Pariisky, 1961) is included in the Wahr model and should no more be applied on the observations.

It is why we show, in Table 3, the results of the Superconducting Gravimeter normalized to the Brussels Tidal System with the inertial correction removed (A) together with the Molodensky I (B) and Wahr (C) models corrected for the indirect oceanic effects by using the Schwiderski maps, the Farrell algorithm and a mass conservation proportional to the amplitude (Moens & alii, 1980).

Considering the high internal precision of the Superconducting gravimeter we may consider the variations of the B/A ratio as reflecting the uncertainties on the tidal loading corrections in the semidiurnal band. On M_2 a 5 per cent error may be suspected. From Table 4 which summarizes the results for Belgium and Luxemburg one sees that the discrepancies expressed by the final residue $\overline{X}$ (X, χ) are lower than 0.2 µgal, a value which could corresponds to a 10 per cent error on the load vector. However no systematic pattern is observed in the Belgium - Luxemburg area. We therefore are of the opinion that a 10 per cent uncertainty on the tidal loading computations is overestimated and that 5 per cent is more probable.

It is clear that the amplitudes should be reduced by 0.6 per cent to fit the Molodensky model and by 1.6 per cent to fit Wahr's theory.

As the goal of this profile is only to check a latitude dependence of the tidal factors we may adopt any normalization. We decided to use an improved tidal model fitting very closely the Molodensky I model at Brussels :

$$\delta\,(O_1) = 1.155 \qquad \delta\,(M_2) = 1.186$$

$$\alpha\,(O_1) = 0^\circ\!.0 \qquad \alpha\,(M_2) = 2^\circ\!.7$$

Of course, as the LCZ gravimeters do not have instrumental phase lags, it is only necessary to normalize the amplitudes by fitting the δ (O_1) tidal factor.

5. *Discussion of the results obtained at Kevo*

The agreement between the two LCZ instruments at Kevo is very satisfactory (Table 5). The strongest discrepancy is found for K_1 because with only six months of observations it cannot be separated from the meteorological wave S_1. The observations made with GEO 761 in 1972 are in good agreement with the new ones for O_1 and M_2.

As already stated in the Introduction we should not rely on the semidiurnal waves to study the latitude dependence of the tidal factors. We do probably not know the indirect effects in this area with a precision better than 10 per cent. This represents 0.1 μgal (or one per cent) on the δ (M_2) tidal factor, an uncertainty larger than the expected latitude effect.

However from the observed values of δ (O_1), with the three instruments, we may say that half a per cent decrease between Brussels and Kevo seems to be a realistic order of magnitude (Table 7) while the uncertainty of the load correction is only of the order of 0.1 per cent in the diurnal band.

6. *Discussion of the results obtained at Madrid*

Although our observations have been performed in Madrid, it is interesting to include the results of the nearby station Valle de los Caidos in the Table 6 which provides two more intercomparisons with the Askania 212 gravimeter which has been calibrated in Brussels in 1978 and with the Tidal LaCoste (ET 15) belonging to the Tidal Institute of Bidston (Liverpool). Direct comparison between Valle and Madrid is insured by LCR 434. In any case, the error on the differential tidal loading between the two stations is at least one order of magnitude below the observational errors.(Vieira, R., et. al., 1985)

Here again we give the corrected tidal factors for the main waves. The general agreement is excellent especially for the LCZ gravimeters and ET 15. Considering now the difference with Brussels, we observe a decrease of one per cent on δ (O_1) instead of an increase of half a per cent.

A slight decrease also appears for M_2 but for the semidiurnal band the uncertainty on the loading is at least 5 per cent (see § 4) which corresponds to half a per cent on the δ factors.

7. *Conclusions*

From the results summarized in Table 8 it may be concluded that strong regional anomalies may conceal the latitude dependence. These anomalies more or less compensate each other at a global scale. It is why the effect was discovered by Melchior (1983) in the results of the Trans World Tidal Gravity Profile.

Which anomalies can we suspect ? In Yanshin & alii (1985) the authors show a correlation between the final residue component X cos χ and the heat flow. Cold regions are associated to negative values of X cos χ which correspond to a smaller amplitude of the body tides. Hot regions associated to positive values of X cos χ seem to correspond to larger tidal amplitudes.

Imperfect mass compensation in the oceanic tides may also produce large scale errors in the loading computations but only for semidiurnal tides.

8. *Acknowledgements*

The authors wish to thank Professor P. Melchior who initiated this experience as well as Professor J. Kakkuri and Professor J.M. Torroja for their support during the campaign of measurements.

The Instituto de Astronomia y Geodesia wishes tho thank M. Van Ruymbeke for the successfull transformation of two LaCoste-Romberg gravity meters into zero method instruments.

We are deeply indebted to E. Nurminen at Kevo, R. Laurent and J. Jean at Brussels and C. de Toro at Madrid for their carefull maintenance. The preparation of the data was insured by C. de Toro, J. Jean, L. Vandercoilden and A. Vandewinkel.

Special thanks are due to the director of the Kevo Subarctic Research Station for his hospitality.

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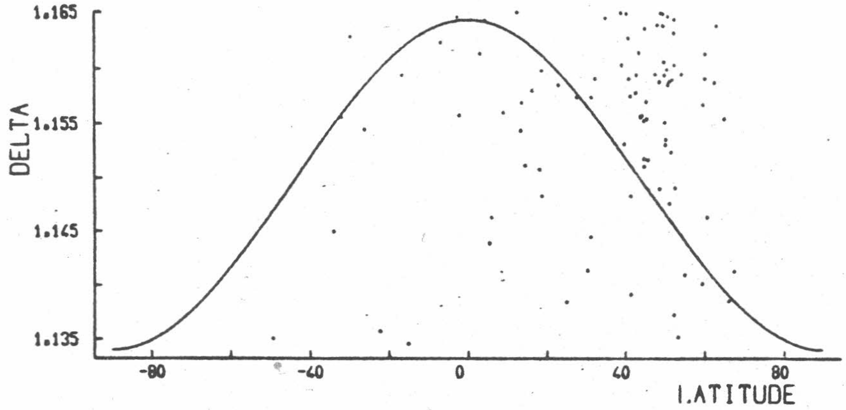

Figure 1 : Répartition of the observations of the Trans World Tidal Gravity profiles compared with the Wahr model (full line).

TABLE 1

Latitude Dependence of the Gravimetric Tidal Factors

diurnal waves : $\delta = \delta_1 + \delta_2 \, (\sqrt{6}/4) \, (7 \sin^2 \phi - 3)$

semi diurnal waves : $\delta = \delta_1 + \delta_2 \, (\sqrt{3}/2) \, (7 \sin^2 \phi - 1)$

	Theoretical model (Wahr, 1980 ; Dehant, 1985)		*Experimental model (Melchior and De Becker, 1983)*	
Wave	δ_0	δ_1	δ_0	δ_1
O_1	1.1520	-0.0065	1.1618 ± 0.0016	-0.0028 ± 0.0015
K_1	1.1320	-0.0063	1.1458 ± 0.0012	-0.0059 ± 0.0013
M_2	1.1599	-0.0045	1.1751 ± 0.0021	-0.0046 ± 0.0010

		ϕ	$\delta(O_1)$	$\delta(K_1)$	Semidiurnal
WAHR	MADRID	40°64	1.1521	1.1321	1.1514
	BRUSSELS	50°80	1.1475	1.1275	1.1460
	KEVO	69°76	1.1404	1.1204	1.1376
MOLODENSKY I			1.1595	1.1376	1.1600.

TABLE 2

Registration Periods

	KEVO		BRUSSELS		MADRID	
LCZ 402	84 04 01	84 09 12	84 01 02	84 03 19	84 10 04	85 03 01
LCZ 487			84 03 30	84 08 24	84 10 10	85 03 01
LCZ 665	84 04 03	84 09 15	84 09 30	85 02 16	85 03 16	85 07 25
GEO 761	72 08 02	72 12 19	73 06 05	73 09 15		

TABLE 3

Comparison of the models at Brussels

	A Brussels Tidal Gravity System without inertial correction		B Molodensky Model + Schwiderski Maps		A/B	C Wahr Model + Schwiderski Maps		A/C
Q_1	1.1629	-0.31	1.1561	-0.23	1.0059	1.1439	-0.24	1.0167
O_1	1.1622	0.04	1.1551	0.03	1.0061	1.1431	0.07	1.0167
P_1	1.1624	0.22	1.1545	0.24	1.0068	1.1432	0.24	1.0168
K_1	1.1493	0.27	1.1398	0.24	1.0083	1.1296	0.24	1.0175
N_2	1.1764	3.05	1.1783	3.09	0.9984	1.1655	3.12	1.0093
M_2	1.1933	2.71	1.1898	2.69	1.0029	1.1771	2.72	1.0138
S_2	1.2074	1.15	1.1968	1.22	1.0089	1.1843	1.24	1.0195
K_2	1.2068	1.34	1.1929	1.12	1.0117	1.1806	1.13	1.0222
M_3^*	1.0753	1.18	1.0700	0.00	0.9988	1.0600	0.00	1.0083

Adjustment of the Amplitudes

	A/B	A/C
Diurnal	1.0068	1.017
Semidiurnal	1.0055	1.016
Proposed	1.0060	1.0165

*No cotidal map available.

TABLE 4

Results for the wave M_2
in Belgium and Luxemburg

Stations	D(km)	B	β	L	λ	X	χ	Q
Veurne	6	1.82	112°	2.00	96°	0.57	-148°	6.3
Gistel	5	1.77	90°	1.97	86°	0.24	-127°	6.8
Damme	10	2.01	69°	1.90	74°	0.19	18°	2.6
Brussel-Bruxelles	110	1.76	61°	1.88	63°	0.13	-92°	54.2
Louvain-la-Neuve	130	2.07	58°	1.88	62°	0.24	26°	7.1
Walferdange	220	1.74	57°	1.84	61°	0.16	-70°	34.0

$\overline{B}$ (B, β) residual vector (observed minus Molodensky I model)

$\overline{L}$ (L, λ) tidal loading computations (Schwiderski maps)

$\overline{X}$ (X, χ) final residue ($\overline{B} - \overline{L}$)

Q quality factor

D distance to the sea

TABLE 5

Results at Kevo

Wave	Theoretical amplitude (microgal)	Tidal loading B (microgal)	β	CORRECTED TIDAL FACTORS LCZ 402 δ	α	LCZ 665 δ	α	GEO 761 δ	α
O_1	20.2	0.24	118°	1.1554	-0.03	1.1549	-0.36	1.1571	-0.43
K_1	28.4	0.30	-78°	1.1436	-0.36	1.1338	0.07	(1.1577)	(-0.36)
N_2	1.7	0.25	89°	1.1356	-0.76	1.1289	-1.13	(1.1769)	(-0.44)
M_2	9.0	1.37	52°	1.1308	0.31	1.1195	0.08	1.1246	0.03
S_2	4.2	0.43	27°	1.1463	-0.65	1.1400	-0.07	(1.0992)	(-0.36)

TABLE 6

Results in Spain a) Valle de Los Caidos

Wave	Theoretical amplitude (microgal)	Tidal loading B (microgal)	β	ET 15 δ	ET 15 α	ASK 212* δ	ASK 212* α	LCR 434 δ	LCR 434 α
O_1	30.72	0.28	-139°	1.1507	0.16	1.1539	-0.01	1.1470	0.17
K_1	43.20	0.34	101°	1.1356	-0.05	1.1236	0.57	1.1414	0.64
N_2	8.28	0.92	120°	1.1581	1.05	1.1648	0.55	1.1626	1.66
M_2	43.25	4.31	101°	1.1599	0.25	1.1613	0.21	|1.1599	0.25|
S_2	20.12	1.51	75°	1.1593	0.12	(1.1293	-0.41)	1.1683	0.10

CORRECTED TIDAL FACTORS: ET 15, ASK 212*, LCR 434.

* Normalized in the Brussel's Improved Tidal System

| | Normalized on ET 15.

b) Madrid

Wave	Theoretical amplitude (microgal)	Tidal loading B (microgal)	β	LCR 434 δ	LCR 434 α	LCZ 402 δ	LCZ 402 α	LCZ 487 δ	LCZ 487 α	LCZ 665 δ	LCZ 665 α
O_1	30.68	0.26	-139°	1.1465	-0.47	1.1483	-0.20	1.1507	-0.32	1.1493	-0.22
K_1	43.15	0.32	101°	1.1399	-0.68	1.1310	-0.16	1.1317	-0.66	1.1361	0.04
N_2	8.33	0.86	119°	(1.1929	1.13)	1.1491	0.27	1.1497	-0.16	1.1432	0.74
M_2	43.49	4.05	100°	1.1577	0.06	1.1573	-0.22	1.1553	-0.29	1.1564	-0.30
S_2	20.23	1.42	74°	1.1623	0.10	1.1584	-0.18	1.1580	-0.03	1.1617	0.09

CORRECTED TIDAL FACTORS: LCR 434, LCZ 402, LCZ 487, LCZ 665.

TABLE 7

Differential latitude effects along the profile
(in per cent of Amplitude factors)

	Madrid	Brussels*	Kevo
Wahr model	+0.46	—	-0.71
Observations δ (O_1)	-1.0	adjusted	-0.4
δ (K_1)	-0.3	+0.2	-0.1

* based on the results of the Superconducting gravimeter (Ducarme et alii, 1985).